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P-T conditions of deformation from fluid inclusions in mylonites

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Abstract

Structural petrology of fluid inclusions in deformed rocks can be used to identify inclusions entrapped during various stages of deformation. Standard thermobarometry on these inclusions can then provide estimates of the P-T conditions of deformation. The application of this technique is illustrated using fluid inclusions in mylonites from the Quetico Fault Zone, Canada. The inferred P,T conditions fall within the P,T field of mylonitisation derived from isotopic, microstructural and phase equilibrium studies.

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INTRODUCTION

In order to fully understand the tectonic evolution of a region we need to integrate detailed studies of the metamorphic P(ressure) -T(emperature) - t(ime) path with geometric and kinematic analysis of both macroscopic and microscopic structures. One approach to integrating the structural and petrologic datasets is to constrain the P,T conditions under which key structures form. Attempts to do this using deformation mechanisms (Knipe 1989) are limited both by the interpretation of microstructures in terms of deformation mechanisms and by the lack of well-constrained deformation mechanism maps.

We here suggest an alternative approach to constraining the P-T conditions of deformation, based on combined studies of the structural petrology and thermobarometry of fluid inclusions. The novelty of our approach lies not in the thermobarometry, which involves standard techniques , but in its application to penetratively deformed rocks. With the exceptions of Kerrich (1976) and Wilkins and Barkas (1978), no work has been done on inclusions in such rocks, probably because the inclusions in such rocks are typically both scarce and small (< 5 μ). We suggest, however, that careful study of the structural setting of these inclusions can be used to develop a chronology of fluid inclusion formation relative to deformation. This chronology, together with fluid inclusion thermobarometry, can then be used to determine the metamorphic conditions prevailing during deformation.

In this note we illustrate the approach with an example from deformed rocks of the Quetico Fault Zone (henceforward QFZ) in the Superior Province of Canada (Fig. 1). We will concentrate on describing the structural petrology of fluid inclusions in these rocks and its implications for the entrapment of inclusions during mylonitisation. The thermobarometric results, and their implications for the regional geology of the QFZ, are discussed in more detail elsewhere (McLellan, submitted to Geology).

GEOLOGICAL SETTING

The scale, sense and timing of motion on the QFZ have been the subject of much debate (see reviews by Borradaile et al. 1988; Percival 1989) but there appears to be consensus that it is a major dextral strike-slip fault with up to 100 km. of displacement. Significant motion on the QFZ had apparently ceased by 2.6 Ga., as palaeomagnetic poles for the adjoining Wabigoon and Quetico subprovinces are coincident from this time forward (Dunlop 1979).

The kinematics of the QFZ have been discussed by Borradaile et al. (1988). They describe early dextral transpression structures subsequently overprinted by a later brittle phase of deformation of the same shear sense. This suggests that movement on the fault occurred during progressive uplift. Microscopic shear sense indicators such as shear bands and quartz c axis fabrics show local variation from outcrop to outcrop (Kennedy 1984) and even within individual hand samples, but such variability seems to result from strain heterogeneity rather than from overprinting by later deformation. There is certainly no correlation between shear sense reversal and metamorphic grade which might indicate fault reactivation (Obee and White 1986).

The western portion of the QFZ lies wholly within the Wabigoon volcanic-plutonic subprovince (Fig. 1), which has been interpreted as an island arc complex (Davis et al. 1988). The QFZ here consists of a relatively wide (up to 1 km thick) zone of mylonites (Kennedy 1984; McLellan, submitted to Geology). Mapping of the QFZ is based on grain size reduction within quartzofeldspathic rocks together with the development of a regionally consistent , E-W striking, subvertical foliation and an associated subhorizontal lineation. Two outcrops in this western portion have been examined in detail as described in the next section.

MESOSCOPIC AND MICROSCOPIC STRUCTURES

Two localities (Fig. 1) have been examined in detail. The Dance Township locality, close to the western extremity of the QFZ, shows deformed granitic gneisses (Fig. 2). It comprises a 500 - 1000 m. thick sequence of ortho- and ultra-mylonites (mylonite terminology from Wise et al. 1984), with ultra-mylonites dominant. Foliation (Fig. 3a) is defined by shape and orientation of feldspar and quartz grains, by fine-scale modal banding of quartzofeldspathic and micaceous minerals and occasionally by grainsize banding. The quartzofeldspathic matrix shows extensive dynamic recrystallisation of quartz, plagioclase and alkali feldspars to a grain size ranging from 0.3 mm. to < 0.1 mm. Elongate porphyroclasts of plagioclase and alkali feldspar, up to 4 mm in grain size, define a lineation in orthomylonites. Both ortho- and proto-mylonites contain dynamically recrystallised quartz ribbons up to 4 mm in length which define a lineation parallel to that formed by feldspar pophyroclasts. In addition to the quartz ribbons, coarser-grained (up to 1 mm grainsize) bands of quartz up to 8 mm in length occur within and parallel to foliation (Fig. 3b). These typically appear less deformed than the quartz in ribbons, and are interpreted to have formed at a later stage of deformation.

The second locality is at Crowrock Inlet, some 50 km. east of the Dance Township locality. Rock types range from quartz diorite to granodiorite and syenite. Enclaves of material interpreted as mafic metavolcanic country rock (S. Shirey, pers. comm.) occur here (Fig. 4), ranging in length up to 0.6 m. Epidote-rich fractures commonly occur in association with these enclaves, and feldspars in these areas show extensive iron-staining. These effects are attributed to local metasomatism. These areas were not sampled in order to avoid possible complications from post-deformational fluid migration. The quartzofeldspathic rocks at Crowrock Inlet are proto- and ortho-mylonites, with proto-mylonites dominant (Fig. 4). Foliation is defined by grain shape and orientation in the quartz and feldspar grains and by layering of micaceous minerals. Microfaults up to 20 - 30 mm. in length cut the mylonitic foliation at a high angle. They show dextral shear sense but have only limited displacement. Pseudotachylite has been described from this locality (Borradaile and Kennedy 1982), but none was found in our samples. The mylonitic matrix shows recrystallised quartz, plagioclase and alkali feldspar of grain size ranging from 0.2 mm to 1.5 mm. Quartz ribbons in the matrix range up to 12 mm in length. Porphyroclasts of alkali feldspar and plagioclase range up to 35 mm and define a weak to strong lineation. Porphyroclasts are normally associated with quartz pressure shadows which show variable recrystallisation (Fig. 5). Some porphyroclasts of alkali feldspar show well-developed core-and-mantle texture. Additionally, some feldspar pophyroclasts are cut by fractures which are parallel to the microfaults observed on outcrop and hand sample scale. There is no obvious displacement across these fractures.

RELATIONS BETWEEN FLUID INCLUSIONS AND MESOSCOPIC STRUCTURES

If we are to use fluid inclusion thermobarometry to constrain the P-T conditions of deformation we require to show that the fluid inclusions were entrapped during deformation. This requires us to distinguish between fluid inclusions inherited from protolith gneisses and those which were formed during mylonitisation. It is well known that inherited fluid inclusion populations are progressively destroyed during subgrain formation and subsequent recrystallisation (Kerrich 1976 and Wilkins and Barkas 1978). Leakage of fluid inclusions during recrystallisation can be recognised from the resulting variability in liquid/vapour ratios (Sisson et al. 1981 and Stockey and McLellan 1988). In general, ultramylonites contain only inclusions which formed during or subsequent to deformation (Stockey and McLellan 1988). Accordingly, our sampling of QFZ material focussed on quartzofeldspathic ortho- and ultra- mylonites and the intrafolial quartz bands within the ultramylonites. We anticipate that inclusions in this material are samples of fluids present during mylonitisation. Additionally, we have oriented samples relative to the lineation defined by porphyroclasts and quartz ribbons. We can thus identify fluid inclusions which occur in fractures normal to this lineation, and we anticipate that these contain fluids present during lineation development. This sampling scheme enables us to establish a spatial correlation between fluid inclusion populations and fault motion-related mesoscopic structures.

However, spatial correlation between fluid inclusions and mesoscopic structures does not necessarily indicate that fluids and deformation were synchronous. There are two possible problems:

(1) An observed spatial correlation between fluid inclusions and microstructures does not necessarily imply a causal connection between these. For example, post-deformational fluids may take advantage of existing structural pathways. We will discuss this further in the next section.

(2) Even if it can be shown that fluids were broadly contemporaneous with deformation it may be vital to know which stage of deformation correlates with a given inclusion population. This is particularly true where structures are reactivated, but as noted above this is not a concern for the QFZ.

RELATIONS BETWEEN FLUID INCLUSIONS AND MICROSCOPIC STRUCTURES

In this section we will consider in more detail the microstructural settings of these populations and their implications for the chronology of deformation and fluid inclusion entrapment. Fluid inclusions have been grouped into populations (types A - D) on the basis of their relation to microstructures as summarised below. A population is defined as a group of inclusions which show consistency of structural setting, size, shape and degree of fill. The characteristics of populations A - D are summarised in Table 1.

Type A inclusions

These occur in Dance Township samples only and are restricted to ultramylonites where they occur as isolated inclusions or clusters in the cores of recrystallised quartz grains (Fig. 6a). The restriction to ultramylonites is compatible with entrapment during mylonitisation. The lack of type A inclusions near grain boundaries suggests that this population was partially destroyed by grain boundary migration during recrystallisation and therefore predates the final fabric-forming event. Type A inclusions are therefore interpreted as forming during dynamic recrystallisation associated with mylonite formation.

Type B inclusions

These inclusions occur in Dance Township ortho- and ultra- mylonites along transgranular fractures which cross the mylonitic foliation (Fig. 6b). Additionally, they occur within the intrafolial quartz bands as trails in fractures which are perpendicular to the lineation defined by the bands (Fig. 6c). Their occurrence in syn-lineation fractures suggests them to be syn-deformational but their transgranular nature suggests that they post-date type A inclusions and presumably also post-date ductile deformation. They may have formed at a late stage of mylonitisation or during uplift.

Type C inclusions

These inclusions occur in Crowrock Inlet samples. They are hosted by recrystallised quartz grains in the proto- and ortho- mylonites. They occur as individual inclusions or as clusters in the cores of grains; grain boundaries are usually empty (Fig. 6d). Type C inclusions often lie along fractures which appear to terminate at the boundaries of the recrystallised grains (Fig. 6e). This suggests that they formed before present grain boundaries were established. Quartz grain boundaries are often lined with decrepitated inclusions (Fig. 6e), interpreted as remnants of inclusions which were destroyed during grain boundary migration. These features suggest that type C inclusions formed during dynamic recrystallisation, analogous to type A inclusions from Dance Township.

Type D inclusions

These occur in all samples of proto- and ortho- mylonite from Crowrock Inlet. They form trails of elongate inclusions occurring in fractures which cut both recrystallised matrix quartz grains and feldspar porphyroclasts (Fig. 6e). These fractures are perpendicular to the lineation defined by feldspar porphyroclasts. By analogy with type B inclusions, type D inclusions are considered to be younger than type C inclusions and to be syn- to post- deformational.

Interpretation

The uniformity of liquid/vapour ratios within populations argues that the inclusions in each population were entrapped as a single homogeneous phase and have not been subsequently modified by necking or decrepitation, i.e. they do not represent an inherited (predeformation) population. No inherited inclusions have been found in these rocks (cf. Stockey and McLellan 1988).

Our preferred interpretation of microstructural relations is that type A and C fluid inclusions formed during dynamic recrystallisation. They therefore record the P-T conditions of that deformation. Types B and D appear to postdate penetrative ductile deformation by an unknown interval. They may, however, provide a minimum P-T estimate for mylonite formation, as follows. Post-fault flushing to produce transgranular trails is more likely to occur when rocks are dilating during uplift than when they are compressing during burial (Norris and Henley 1976). P-T estimates derived from such "late" transgranular inclusions thus record the conditions under which uplift occurred. On a clockwise P-T-t path such as we might expect for a transpressive margin, uplift will occur at lower values of P,T than peak metamorphism and associated deformation. Thus the uplift P-T conditions recorded by transgranular inclusions will represent minimum P-T conditions for mylonitisation. We can obviously test this assertion by comparing the P-T estimates from syn-deformational inclusions (types A and C) with those from post-deformational inclusions (types B and D).

In the next section we show how such P-T estimates are obtained from inclusions.

FLUID INCLUSION DATA

A complete discussion of the techniques used in fluid inclusion analysis can be found in Hollister and Crawford (1981) and Roedder (1984). Briefly, thermobarometric analysis requires the following:

(i) measurement of liquid/vapor homogenisation temperature (T_h), which is a measure of the density of the fluid in the inclusion,

(ii) measurement of the freezing point depression (T_m), which is a measure of the chemical composition of the fluid in the inclusion,

(iii) calculation of the isochore (line of equal density in P-T space) from (i) and (ii) and plotting of this isochore on a P-T grid.

Compositions and densities of inclusions in QFZ samples have been measured by standard microthermometric techniques on a "Fluid Inc." heating- freezing stage. The stage is calibrated using the triple points of H_2O and CO_2 in synthetic pure H_2O and H_2O - CO_2 inclusions. Accuracy is $\pm 0.1^\circ C$. Reproducibility of individual measurements is a function of inclusion size, but on inclusions larger than 2 μ we obtain reproducibility of $\pm 0.2^\circ C$.

Homogenisation temperature data for each of the four inclusion types A - D are shown in Table

2 and Fig. 7. The clustering of data on the histograms (Fig. 7) supports our interpretation that each of types A - D is a homogeneous single population. The freezing point data in Table 2 indicate that all of the analysed inclusions in populations A - D are H_2O - NaCl fluids. Isochores for these fluids have been determined from the T_m and T_h data in Table 2 using the salinity equations of Potter and Brown (1977) and the modified Redlich-Kwong equation of state derived by Holloway (1981). Figure 8 is a P-T plot of the resulting isochores.

P-T CONDITIONS OF DEFORMATION

Type A and C inclusions occur within grains formed during recrystallisation, thus if we are correct in our interpretation that type A and C inclusions sample fluids present during this recrystallisation, the isochores for A and C must pass through the P-T conditions of deformation. Similiarly, type B and D inclusions occur in transgranular trails which must have formed when penetrative ductile deformation had ceased and been replaced by local brittle failure. The isochores for types B and D must therefore pass through the range of P-T conditions appropriate for this brittle deformation. Thus the isochores on Fig. 8 indicate the possible ranges of P and T for two different stages (brittle and ductile) in the history of the QFZ.

The location of the isochores on Fig. 8 provides valuable information even if we cannot accurately define our position on that isochore. On the basis of microstructural setting we interpret population: A to be older than population C and likewise B to be older than D. Given this chronology, we can constrain P-T-t paths for each of the two outcrops, as shown (Fig. 8). The steep slope of these P-T-t paths indicates that the thermal history of this segment of the QFZ was dominated by conductive cooling during uplift rather than by any convective input from circulating fluids (Hames et al. 1989). This is in contrast to other sections of the QFZ where convection-dominated P-T-t paths are recorded in the vicinity of known and suspected ore deposits (McLellan, unpublished data). The lower P-T regions occupied by isochores of type B and D inclusions compared to types A and C inclusions supports our petrographic interpretation that types B and D formed during uplift subsequent to penetrative deformation. The difference in P-T regime between deformation and uplift is small, suggesting that type B and D inclusions formed very soon after ductile deformation. The differences in the P,T locations of the isochores from the two localities are greater than could be attributed to errors in the data, and so appear to be real. This suggests that deformation occurred under different P,T conditions along the length of the fault. The implications of this for fault geometry are explored elsewhere (McLellan, submitted to Geology).

DISCUSSION

In order to evaluate the usefulness of fluid inclusion thermobarometry, we need to test the reliability of the results. In this section, we compare our results with independent estimates of the P,T conditions of deformation and metamorphism in the study area and in other mylonite occurrences.

It is of interest to compare the P-T conditions inferred for deformation on this segment of the QFZ to the P-T conditions inferred for the adjoining subprovinces. Poulsen et al. (1980) show "sillimanite-muscovite grade" conditions for Wabigoon rocks in the study area but give no values of P and T. Unfortunately, most of the detailed petrologic studies have focussed much further east where the QFZ is complicated by greater structural and lithologic diversity. For example, Percival (1989) quotes P = 2.5 kb and T = 500°C for the Poohbah Lake area, approximately 100 km. to the southeast of our study area. However, Poohbah Lake lies in the Quetico subprovince and it is not clear how metamorphic conditions in the Quetico subprovince relate to those in the Wabigoon subprovince of the study area.

We also must consider how our P,T estimates for mylonitisation compare with those of other workers in other areas. Obviously, mylonitisation can occur over a range of crustal levels and there will be no single set of P,T conditions applicable to all mylonites. The P - T region lying between the type B and C isochores on Fig. 8 represents the extreme range of deformation conditions recorded in the QFZ samples studied. This region has been transferred to Fig. 9 for comparison with estimates of other workers for the P-T conditions needed for mylonite formation. These estimates have been derived using a variety of approaches: (i) oxygen isotope geothermometry (Sinha et al. 1986, Kerrich and Rehrig 1987, McCaig 1988), (ii) phase assemblages in wall rocks (Anderson 1988 and Saltzer and Hodges 1988), (iii) resetting of isotopic systems (Sinha and Glover 1978 and O'Hara and Gromet 1983) and (iv) qualitative estimates from deformation mechanisms (O'Hara and Gromet 1983 and Simpson 1985). Only the latter are directly tied to deformation, and they are necessarily imprecise as deformation mechanisms are not solely dependent on P and T.

The P,T field of mylonitisation deduced for the Quetico samples from fluid inclusion thermobarometry shows considerable overlap with the estimates of other workers. This suggests that the technique may be of value in circumstances where other methods are insufficiently precise (as appears to be generally true for deformation mechanisms) or not applicable (for example, regions lacking the low-variance mineral assemblages needed for phase equilibrium studies). Our estimates of deformation conditions lie on the high-temperature side of estimates based on oxygen isotopes, which suggests that oxygen isotope thermometers may record only the retrograde evolution of shear zones.

In summary, it appears that fluid inclusion thermobarometry on these samples provides P,T estimates which are compatible with independent estimates of both the conditions of regional metamorphism and the conditions of mylonitisation. The resolution afforded by this technique additionally allows us to track variations in the P,T conditions of deformation along the fault.

CONCLUSIONS

Fluid inclusion thermobarometry can provide an accurate method for determining the P,T conditions of deformation if care is taken to document the mesoscopic and microscopic setting of the inclusions. Reliable estimates can be obtained from inclusions preserved in the cores of recrystallised quartz grains in mylonites. Analysis of fluid inclusions in Quetico Fault Zone mylonites indicates P,T conditions of deformation which overlap with estimaes from isotopic, microstructural and phase equilibrium studies. Fluid inclusion analysis, however, can be used under circumstances where other techniques are not applicable. Additionally, the technique provides greater resolution than existing methods and can be used to document variations in the P,T conditions of deformation along the length of a fault zone.

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TABLE 1. CHARACTERISTICS OF FLUID INCLUSIONS FROM QFZ

Sample site [a]	Inclusion type	Petrography of host quartz	Occurrence of inclusions	Size (μ)	Phases [b]
DT	A	Recrystallised grains in ultramylonite	Isolated or clusters in cores of grains	2	L + V
DT	B	Recrystallised grains in ultramylonite, intrafolial quartz bands	Transgranular trails in fractures normal to lineation	2	L + V
CR	C	Recrystallised grains in mylonite	Clusters, or trails which terminate at grain boundaries	2 - 5	L + V
CR	D	Recrystallised grains in mylonite	Transgranular trails in fractures normal to lineation	2	L + V

[a] DT = Dance Township, CR = Crowrock Inlet

[b] L = liquid, V = vapour

TABLE 2. SUMMARY DATA ON FLUID INCLUSIONS FROM QFZ

Inclusion type (see table 1)	Number of analyses	T_h (range) (°C)	(mean)	T_m (range) (°C)	(mean)
A	38	279 - 312	(293)	- 7 .2 to - 5.6	(- 6 .3)
B	16	289 - 314	(302)	-7 .5 to -6 .3	(- 7.1)
C	36	222 - 252	(238)	- 14 .1 to - 11.6	(- 12 .6)
D	20	238 - 251	(247)	-13.0 to -11 .9	(-12.2)

FIGURE CAPTIONS

Figure 1. Location of QFZ and sample sites. DT = Dance Township, CR = Crowrock Inlet.

Figure 2. Outcrop view of Dance Township locality. Note the well-defined mylonitic banding defined by grainsize and modal variations.

Figure 3. Microstructures from Dance Township.

Figure 3a. Ultramylonite from Dance Township. View of recrystallised quartzofeldspathic matrix in ultramylonite, showing grain shape elongation and dynamic recrystallisation of quartz and feldspar. Field of view is 3mm. Crossed polars.

Figure 3b. Intrafolial quartz band from ultramylonite, Dance Township. Quartz appears clear and fine-grained micaceous matrix appears dark. Grain boundaries are visible within the quartz bands. Field of view is 3 mm., PPL (thick section).

Figure 4. Outcrop view of Crowrock Inlet locality. Note dominance of protomylonite with large porphyroclasts of alkali feldspar and presence of elongate enclave of mafic metavolcanic material.

Figure 5. Microstructures from Crowrock Inlet. Porphyroclast of alkali feldspar in ortho-mylonite. Note dynamic recrystallisation of quartz and feldspar in the surrounding matrix, also the quartz pressure shadow which exhibits more limited recrystallisation. Field of view is 3 mm., crossed polars.

Figure 6. Structural petrology of fluid inclusions.

Figure 6a. Type A fluid inclusions, ultramylonite, Dance Township. Inclusions occur in clusters in the cores of recrystallised quartz grains. PPL, field of view is 0.1 mm.

Figure 6b. Type B fluid inclusions, ultramylonite, Dance Township. Transgranular trail cuts recrystallised quartz grains in ultramylonite. PPL, field of view is 0.2 mm.

Figure 6c. Type B fluid inclusions, intrafolial quartz band, ultramylonite, Dance Township. Small intrafolial quartz band shows clear against darker micaceous matrix. Fluid inclusions occur in fractures perpendicular to length of band. PPL, field of view is 3 mm.

Figure 6d. Type C fluid inclusions, ortho-mylonite, Crowrock Inlet. Inclusions occur as clusters in cores of recrystallised quartz grains. Note that grain boundaries are empty. PPL, field of view is 0.5 mm.

Figure 6e. Type C and D fluid inclusions, orthomylonite, Crowrock Inlet. Type C inclusions are intragranular trails which stop before grain boundaries. Type D inclusions are transgranular trails. Note that grain boundaries are commonly decorated with decrepitated inclusions, believed to be remnants of type type C inclusions. PPL, field of view is 0.1 mm.

Figure 7. Histograms showing homogenisation temperature (T_m) data for inclusions from each of the populations A - D.

Figure 8. Isochores for fluid inclusions of types A - D shown in P - T space. If the fluids in these inclusions were trapped during deformation, the P-T region between (shaded) represents the P,T conditions of deformation. The region between A and C corresponds to mylonite formation by ductile recrystallisation. the region between B and D corresponds to brittle deformation, presumably during regional uplift. The open arrows represent P-T-t paths for the two study localities (DT = Dance Township, CR = Crowrock Inlet). The slope of the paths is constrained by the requirement that at any locality the arrow must pass through older isochores before passing through younger, i.e.

at Dance Township it must pass A before B and at Crowrock Inlet it must pass C before D.

Figure 9. The P,T conditions for formation of QFZ mylonites (labelled "(P,T) mylonitisation, this study") compared to P,T estimates for mylonitisation from other workers. These estimates are derived from:

1 - oxygen isotope thermometry (Sinha et al. 1986, Kerrick and Rehrig1987, McCaig 1988),

2 - phase assemblages in wall rocks; 2a from Anderson, 1988, 2b from Saltzer and Hodges 1988,

3 - reseting of isotopic systems (Sinha and Glover 1978, O'Hara and Gromet 1983),

4 - deformation mechanisms (O'Hara and Gromet 1983, Simpson 1985).

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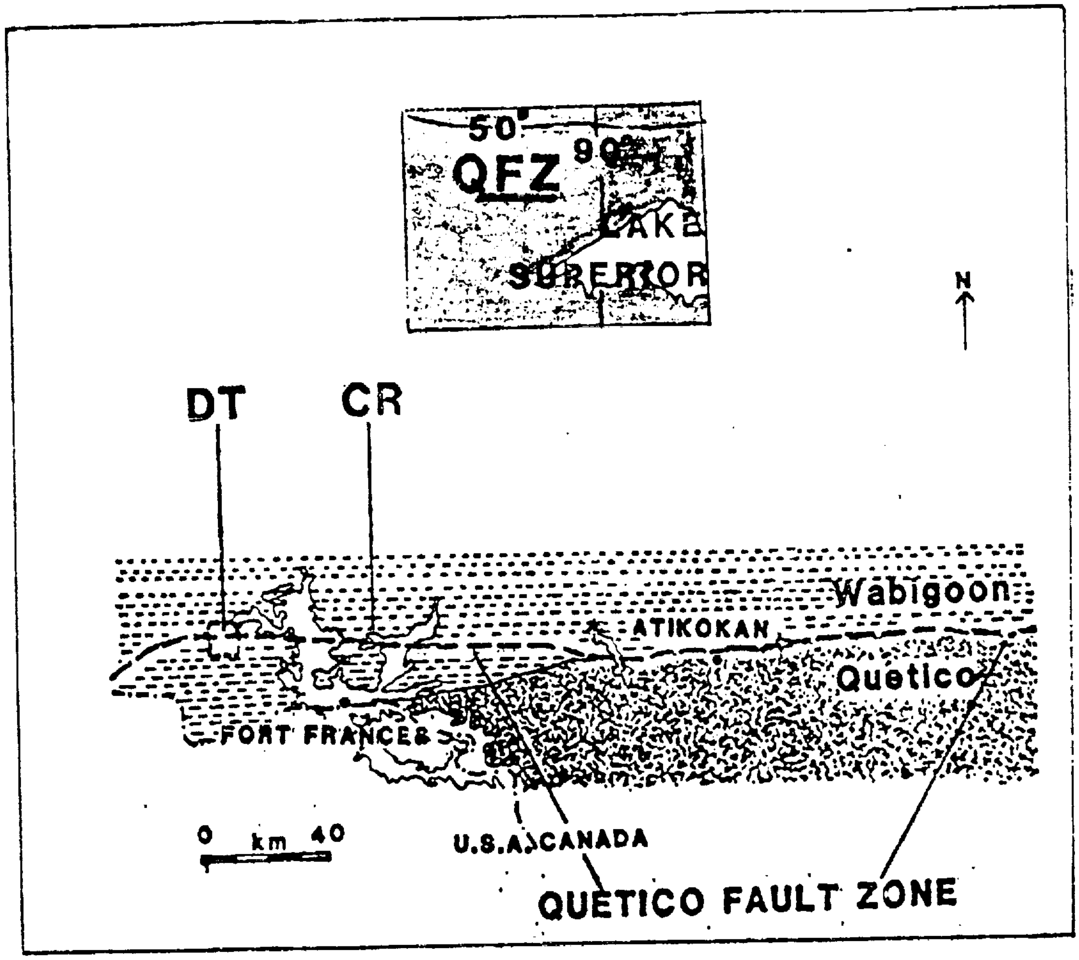

McLellan
Fig. 1

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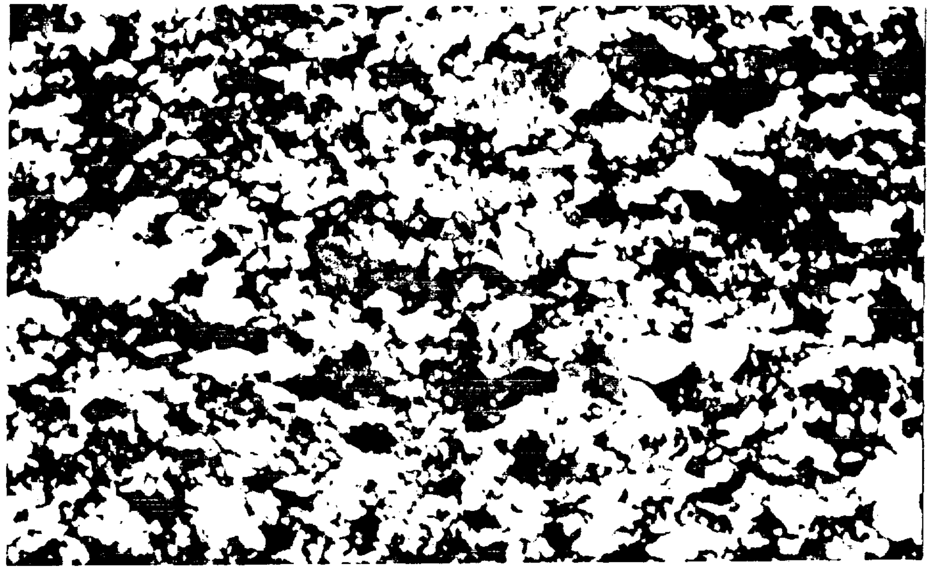
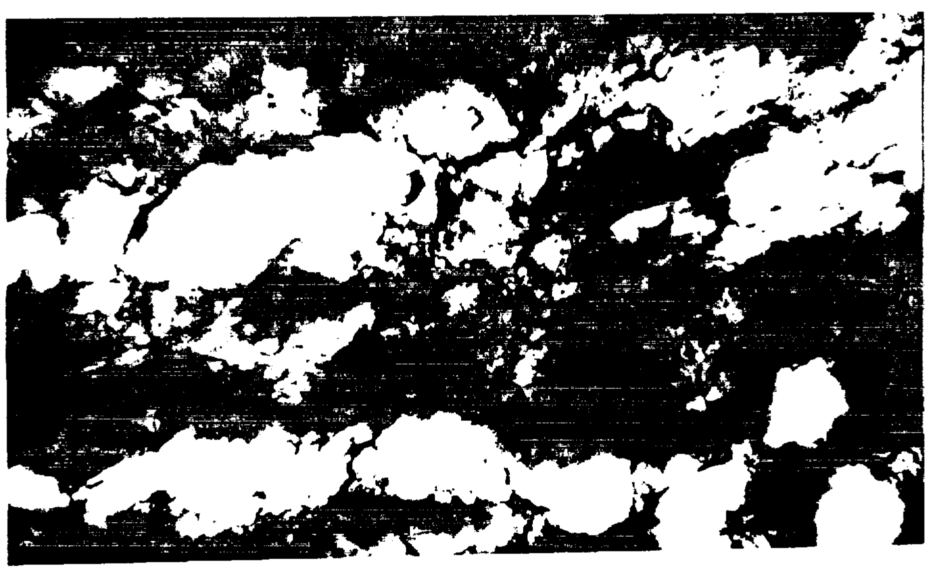


(a)



(b)

McClellan
Fig 3

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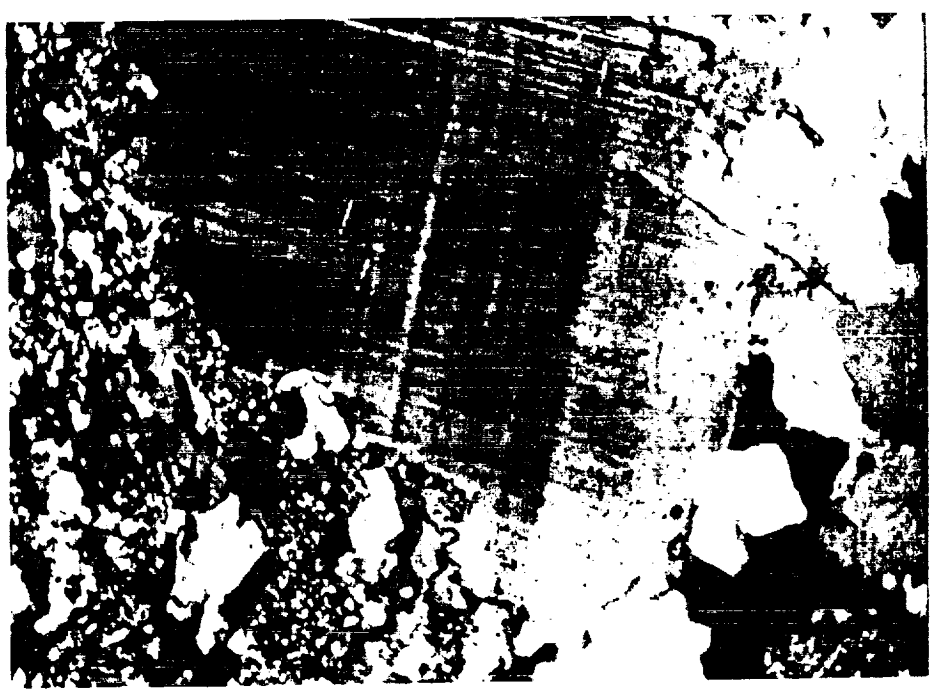
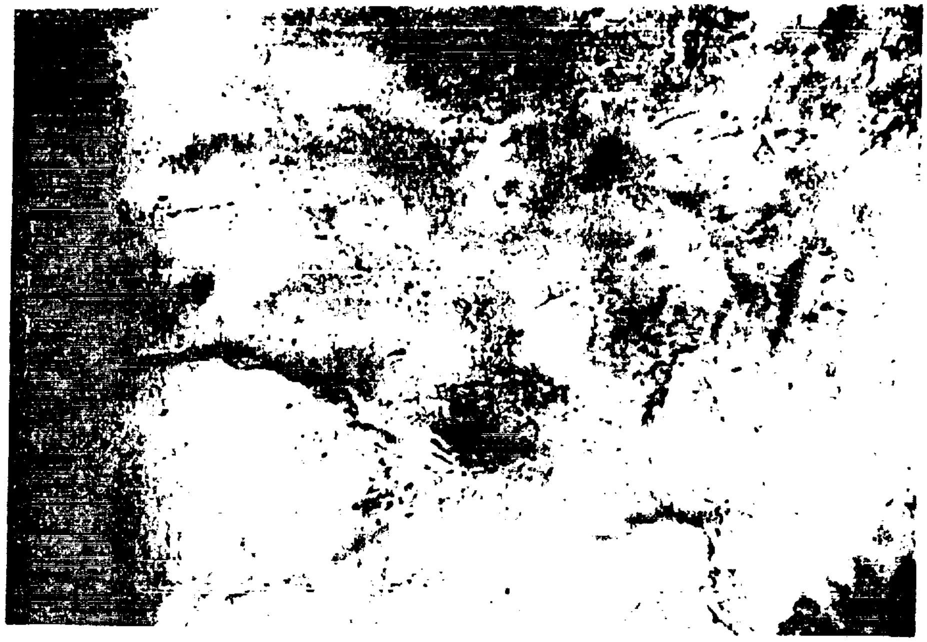
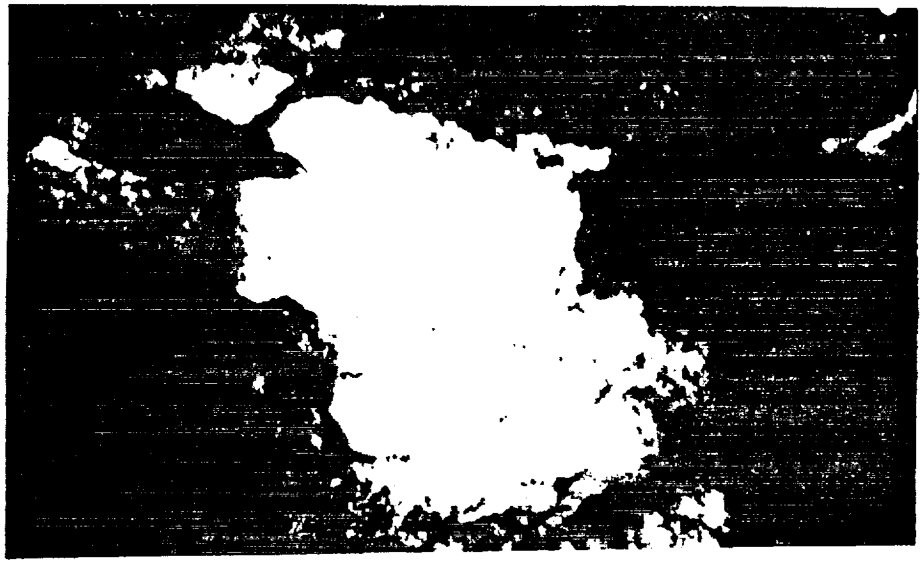




6(b)

6(c)



6(d)

6(e)

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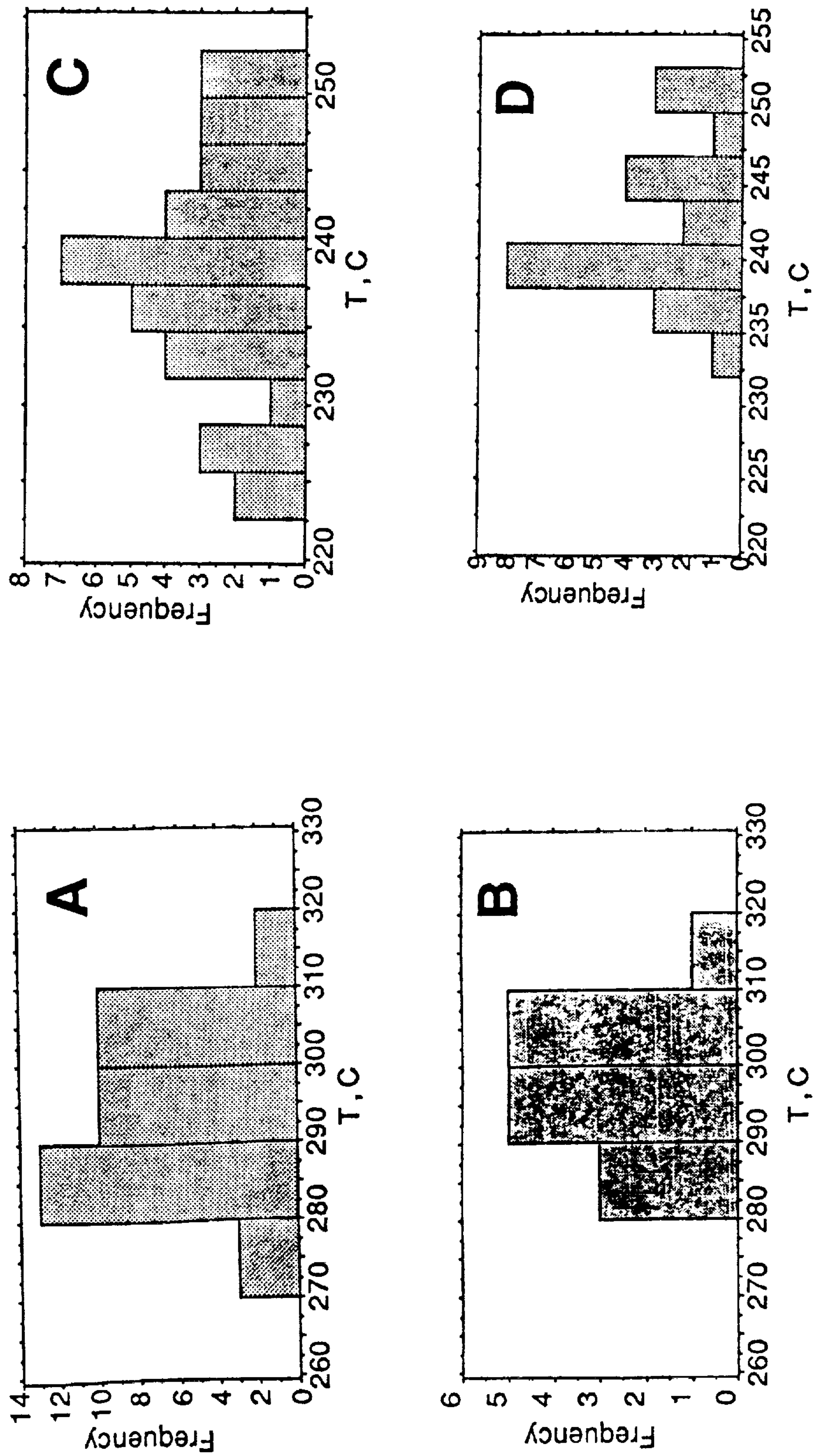

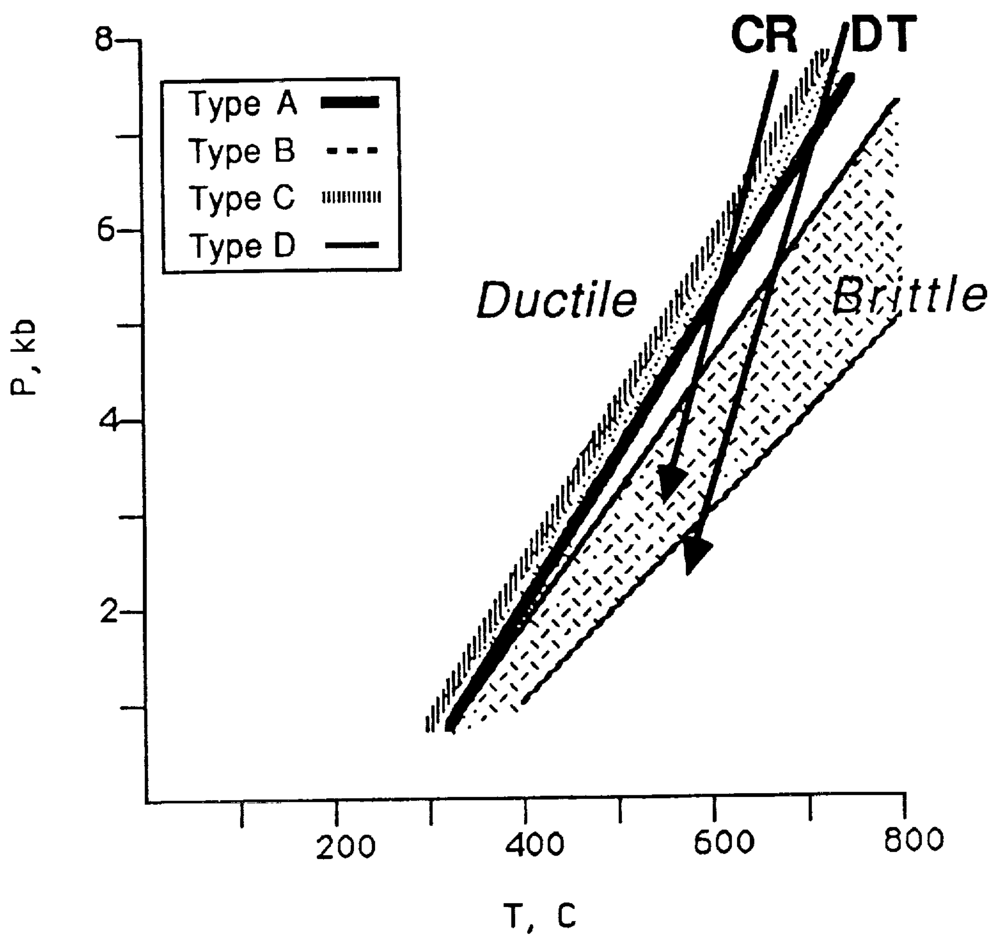
CR
DT
Type A
Type B
Type C
Type D
Ductile
Brittle
P, kb
8
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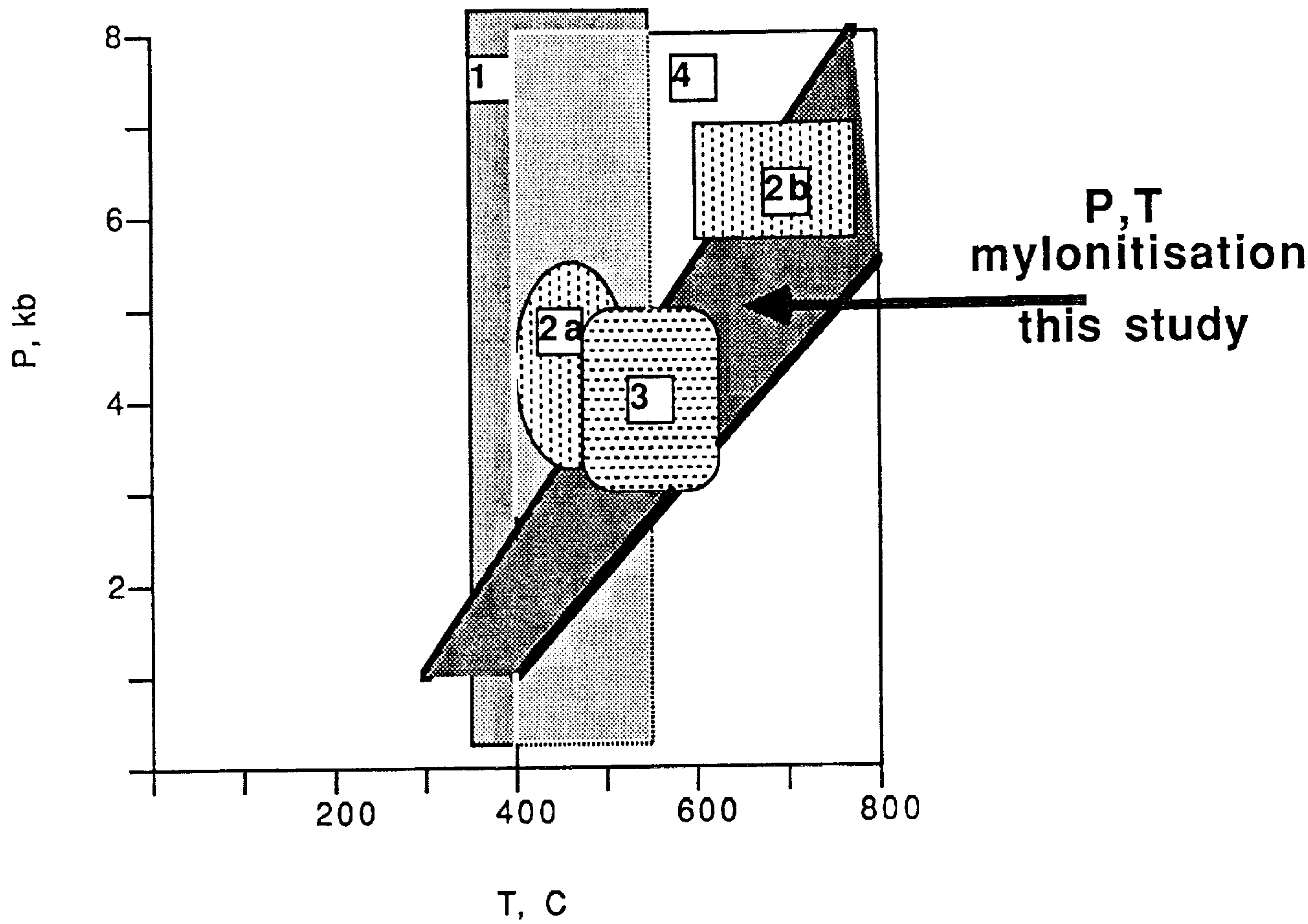
T, C



8
6
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P, kb
200
400
600
800
T, C
1
2a
2b
3
4
P,T
mylonitisation
this study